

AN UPDATE ON χ_c DECAYS: PERTURBATIVE QCD VERSUS DATA

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Abstract

We present a global fit of current available experimental results on χ_c decays within next-to-leading-order perturbative QCD. The quality and reduced errors of recent data improve the agreement between theory and experiment.

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The study of charmonium has recently received renewed interest. All aspects, from spectroscopy, to decays and production have benefited from new data and novel theoretical developments. Recent experimental data concern measurements of total [1, 2] and radiative decay widths [3, 4, 5], the observation of the 1P_1 state [6], measurements of decay branching ratios of B mesons into P-wave charmonium states [7], production cross sections in hadronic collisions, both at fixed target [8] and at collider energies [9, 10, 11]. New theoretical developments cover, among other things, attempts to extract the value of α_s from lattice QCD calculations of quarkonium decay widths [12], the development of a systematic approach to the problem of infrared ambiguities in the production and decay of P-wave states [13, 14], discovery of new production mechanisms at high p_t [15]. The large disagreement observed between expected and measured production rates at the Tevatron [10], has also led to new speculations about the existence of exotic spectroscopy in the charmonium system [16]. We believe that this discrepancy provides an important arena in which to test our understanding of the boundary domain between perturbative and non-perturbative QCD. In this respect, it is fundamental to derive the best possible perturbative predictions, in order to be able to firmly assess the need for, and to properly model, possible additional non-perturbative phenomena required for a complete description of this physics. With this goal in mind, we recently completed a full next-to-leading-order (NLO) calculation for the total production cross section of $^3P_{0,2}$ states in hadronic collisions. A consistent use of this calculation, requires the inclusion of phenomenological parameters extracted from a NLO analysis of inclusive decay widths of these states. In this letter, we therefore present an updated comparison between QCD predictions for the decay widths of 3P_J (χ_{cJ}) states and the latest experimental data. We will not include the 1P_1 state here, as the available data are still insufficient.

Several detailed studies of this subject have appeared in the past [17, 13, 18, 19]. We feel that the new data justify an update. Furthermore, we improve the commonly used expression for the decay width of the χ_{c1} state to light hadrons [20], with the inclusion of a finite $\mathcal{O}(\alpha_s^3)$ term which has usually been neglected.

We will show that the inclusion of all available data, in addition to relaxing some theory constraints used in the literature so far, allows a consistent global fit in terms of three parameters. The first parameter is simply α_s , the QCD coupling constant. The second parameter, $|R'(0)|^2$, corresponds to the derivative of the non-relativistic P-wave function at the origin. The third parameter is required to regulate the infrared divergency which appears in the standard calculation of P-wave decays to a $gq\bar{q}$ final state. This parameter is an infrared cutoff, usually loosely referred to as the binding energy E_{bind} . It appears in the standard expression for the decay widths [20] as a factor $L = \log[4m_c^2/(4m_c^2 - M^2)] = \log(M/2E_{bind})$, where m_c is the constituent charm quark mass. In the recent formulation of P-wave decays introduced in ref. [13], this logarithm is absorbed into the color octet, 3S_1 component of the $c\bar{c}$ wave function, which turns out to be proportional to the combination $\alpha_s|R'(0)|^2L$. As discussed in [14], this relation provides a solid basis for the study of higher order perturbative corrections, as well as providing a rigorous framework to regulate IR divergencies appearing in the evaluation of the $q\bar{q} \rightarrow g\chi_J$ cross section.

We shall start by collecting here the expressions for NLO χ decay widths [20] that will

be used in our fit:

$$\Gamma(\chi_J \rightarrow \gamma\gamma) = A_J^{\gamma\gamma} e_Q^4 \alpha_{em}^2 \frac{|R'(0)|^2}{m_c^4} \left(1 + B_J \frac{\alpha_s}{\pi}\right) \quad (J = 0, 2) \quad (1)$$

$$\Gamma(\chi_J \rightarrow LH) = A_J^{gg} \alpha_s^2 \frac{|R'(0)|^2}{m_c^4} \left(1 + C_J \frac{\alpha_s}{\pi}\right) + \pi \alpha_s^2 H_8 \quad (J = 0, 2) \quad (2)$$

$$\Gamma(\chi_{c1} \rightarrow LH) = -\frac{56n_f}{27} \alpha_s^2 \frac{\alpha_s}{\pi} \frac{|R'(0)|^2}{m_c^4} + \pi \alpha_s^2 H_8 \quad (3)$$

where:

$$A_0^{\gamma\gamma} = 27 \quad A_2^{\gamma\gamma} = \frac{36}{5} \quad B_0 = \frac{\pi^2}{3} - \frac{28}{9} \quad B_2 = -\frac{16}{3} \quad (4)$$

$$A_0^{gg} = 6 \quad A_2^{gg} = \frac{8}{5} \quad C_0 = 8.772 \quad C_2 = -4.827 \quad n_f = 3 \quad (5)$$

To follow the spirit Ref. [13], we introduced the parameter H_8 , which we *define* as:

$$H_8 = \frac{8n_f}{9\pi} \frac{\alpha_s}{\pi} \frac{|R'(0)|^2}{m_c^4} L \quad (6)$$

The precise connection between this parameter and the color octet wave function, can be found in [13].

Following the suggestion of [14], we chose to scale the widths by the charm constituent quark mass, m_c , rather than by the mass of the quarkonium states. This is consistent with the neglect of higher order non-relativistic (NR) corrections, and with the inclusion of all non-perturbative effects into $|R'(0)|^2$. Since $|R'(0)|^2$ and m_c always appear in the fixed combination $|R'(0)|^2/m_c^4$, the precise value of the charm mass will not change the fitted value of the other two free parameters, α_s and H_8 . It is important to point out, furthermore, that it is possible to make consistent use of the extracted value of $|R'(0)|^2$ in the calculation of production cross sections, by properly identifying the origin of the mass terms present in the theoretical cross sections. For example, LO direct P -wave production cross sections are proportional to $|R'(0)|^2/M^7$. Of the seven powers of mass, four have the same origin as those appearing in the decay widths. The remaining three are from phase space. It is therefore consistent to write the overall factor appearing in production as $|R'(0)|^2/16m_c^4/M^3$, where M is the charmonium state mass. With this choice, no ambiguity in the choice of m_c arises when using our fitted values in the study of production cross sections.

In our expressions we neglected the very small contribution of the 3 gluon decay of the χ_{c1} [19]. We included however a finite, non-logarithmic contribution to $\Gamma(\chi_{c1} \rightarrow LH)$, which was not evaluated in the original calculation [20]. To our knowledge this piece has always been neglected in previous studies ². It turns out that this term is not numerically

²We thank E. Braaten for pointing out this fact and suggesting we evaluate and include this contribution.

negligible when compared to the formally dominant logarithm, and should therefore be included.

Corrections to the NR approximation are not known, but are expected to at least partly cancel when taking ratios of widths. In a recent series of papers [18], Consoli and Field argued that by properly taking into account the phase space reduction due to the effective mass of the gluon, it is possible to provide a consistent perturbative description of the decay widths of charmonium and bottomonium S-wave states, without need for the inclusion of significant NR corrections. This is consistent with the observation that EM decays (such as $\eta_c \rightarrow \gamma\gamma$ or $\psi \rightarrow \ell^+ \ell^-$) are correctly predicted if the $O(v^2)$ corrections are set to 0. It is not known whether this applies to P -waves as well, but we will comment on the consequences of these ideas for our fits of χ decays at the end.

Taking ratios or differences of appropriate widths, can lead to expressions which are independent of $|R'(0)|^2$ or H_8 , or both. These ratios can be used to estimate with smaller theoretical uncertainty the only really perturbative parameter of the theory, namely α_s . Some examples which are often used in the literature are:

$$\frac{\Gamma(\chi_{c0} \rightarrow \gamma\gamma)}{\Gamma(\chi_{c2} \rightarrow \gamma\gamma)} = \left(\frac{15}{4}\right) \frac{1 + \frac{\alpha_s}{\pi} B_0}{1 + \frac{\alpha_s}{\pi} B_2} \quad (7)$$

$$\frac{\Gamma(\chi_{c0} \rightarrow LH) - \Gamma(\chi_{c1} \rightarrow LH)}{\Gamma(\chi_{c2} \rightarrow LH) - \Gamma(\chi_{c1} \rightarrow LH)} = \left(\frac{15}{4}\right) \frac{1 + (8.772 + 28/27) \frac{\alpha_s}{\pi}}{1 + (-4.827 + 35/9) \frac{\alpha_s}{\pi}} \quad (8)$$

$$\frac{\Gamma(\chi_{c0} \rightarrow \gamma\gamma)}{\Gamma(\chi_{c2} \rightarrow LH) - \Gamma(\chi_{c1} \rightarrow LH)} = \left(\frac{135}{8}\right) e_Q^4 \left(\frac{\alpha_{em}}{\alpha_s}\right)^2 \frac{1 + \frac{\alpha_s}{\pi} B_0}{1 + (-4.827 + 35/9) \frac{\alpha_s}{\pi}} \quad (9)$$

$$\frac{\Gamma(\chi_{c2} \rightarrow \gamma\gamma)}{\Gamma(\chi_{c2} \rightarrow LH) - \Gamma(\chi_{c1} \rightarrow LH)} = \left(\frac{9}{2}\right) e_Q^4 \left(\frac{\alpha_{em}}{\alpha_s}\right)^2 \frac{1 + \frac{\alpha_s}{\pi} B_2}{1 + (-4.827 + 35/9) \frac{\alpha_s}{\pi}} \quad (10)$$

Notice that the inclusion of the non-logarithmic contribution to $\Gamma(\chi_{c1} \rightarrow LH)$ (the factor 35/9 appearing in the above equations) significantly reduces the $\mathcal{O}(\alpha_s^3)$ corrections to the difference $\Gamma(\chi_{c2} \rightarrow LH) - \Gamma(\chi_{c1} \rightarrow LH)$.

In reference [13] the value of α_s was extracted from the measurement of bottomonium decays, evolved down to the charm mass. This implicitly assumes that α_s has to be evaluated at the scale of the heavy quark mass, and led to a value of $\alpha_s(m_c) = 0.25 \pm 0.02$ at $m_c = 1.5$ GeV. We prefer instead to leave α_s as a free parameter, to be fit together with $|R'(0)|^2/m_c^4$ and H_8 . In fact we believe that the safest and less restrictive assumption on the scale of α_s is that it has to be same for all decay processes, therefore enabling us to use the same value of α_s regardless of J and of the final state. This choice is also free of ambiguities related to the actual value of m_c . While this will not allow us to extract a value of Λ_{QCD} , it provides however a less restrictive constraint on the comparison of data with QCD. We will verify at the end that the fitted value of α_s is in reasonable agreement with what expected fixing the renormalization scale to be of the order of the charm mass.

Another choice performed in [13] was to use only the leading order (LO) version of equations (7)-(10). This was justified by the fact that the contributions to decay widths via the color-octet 3S_1 component of the wave function are only known to LO. However, higher order corrections to the terms proportional to H_8 do not depend on J , as they arise from the S -wave component of the wave function [14]. We can absorb these universal higher order corrections into the parameter H_8 , so that their effect does not change the results of the fit for the variables α_s and $|R'(0)|^2$. We therefore feel that it is justified to use the full $\mathcal{O}(\alpha_s^3)$ expressions given above.

We collect the data that will be used in our fit in Table 1. We notice that a key measurements, namely $\Gamma(\chi_{c0} \rightarrow \gamma\gamma)$, was never actually published [21]. The large error associated to it will not weigh this measurement significantly in our fit, which is unfortunate since the ratio of the photonic widths of the even χ states is a very good probe of the theory. The other debated item is $\Gamma(\chi_{c2} \rightarrow \gamma\gamma)$, whose central value differs significantly among various experiments [3, 4, 5] (we do not quote previous older results, some of which are simply upper limits). It is not our duty to judge on the value of the experimental data, so we chose, contrary to other authors [18], to include them all and let the associated errors drive the fit.

We provide here the results of the fit to these seven measurements, using the theoretical widths provided in equations (1)-(3):

$$\alpha_s = 0.286 \pm 0.031 \quad \frac{|R'(0)|^2}{16m_c^4} = 0.60 \pm 0.10 \text{ MeV} \quad H_8 = 4.2 \pm 0.7 \text{ MeV} \quad (11)$$

$$H_1 = 13.7 \pm 2.3 \text{ MeV} \quad \chi_{fit}^2 = 7.1 \quad (12)$$

The total χ^2 of the fit is 7.1 for the four degrees of freedom. The poor quality of the fit is mostly due to the discrepancy between the different measurements of $\Gamma(\chi_{c2} \rightarrow \gamma\gamma)$. We included, for reference, also the numerical value of H_1 , defined in [13] as:

$$H_1 = \frac{9}{2\pi} \frac{|R'(0)|^2}{m_c^4} \quad (13)$$

We notice that the value of α_s returned by the fit is consistent with $\alpha_s(m_c) = 0.30$, obtained at two loops using $m_c = 1.5 \text{ GeV}$ and the value of $\Lambda_4^{2-loop} = 235 \text{ MeV}$ extracted from DIS data [22]. The value of the derivative of the wave function is also consistent with potential model calculations (see for example the recent update in ref. [23]).

In Table 2 we provide the distribution of differences between expected and measured decay widths, relative to the experimental errors, for the seven measurements considered. The theoretical values are obtained using the fitted values of parameters. It is interesting to see what happens if one of the two best measurements of $\Gamma(\chi_{c2} \rightarrow \gamma\gamma)$ is removed from the fit. Removing the CLEO data point gives as central values for the fit :

$$\alpha_s = 0.298 \pm 0.034 \quad \frac{|R'(0)|^2}{16m_c^4} = 0.55 \pm 0.11 \text{ MeV} \quad H_8 = 3.9 \pm 0.7 \text{ MeV} \quad (14)$$

$$H_1 = 12.6 \pm 2.3 \text{ MeV} \quad \chi_{fit}^2 = 3.5 \quad (15)$$

The central values have not changed significantly from the global fit, but the χ^2 is now consistent with the 3 remaining degrees of freedom. The CLEO measurement in this case would be off by less than 2 sigma from the theoretical expectation.

Removing the E760 data point gives as central values for the fit :

$$\alpha_s = 0.195 \pm 0.031 \quad \frac{|R'(0)|^2}{16m_c^4} = 1.23 \pm 0.3 \text{ MeV} \quad H_8 = 7.7 \pm 2.1 \text{ MeV} \quad (16)$$

$$H_1 = 28.3 \pm 7.8 \text{ MeV} \quad \chi_{fit}^2 = 3.1 \quad (17)$$

The central values have now moved significantly. The χ^2 has improved, thanks to the larger relative error quoted by CLEO for $\Gamma(\chi_{c2} \rightarrow \gamma\gamma)$. Notice that in this case the value of α_s extracted is consistent with what determined by CLEO in their analysis of their measurement ($\alpha_s = 0.219 \pm 0.127$ [5]). The E760 measurement in this case would be off by about 6 sigma from the theoretical expectation based on the values of parameters extracted from the fit.

In Table 3 we present the comparison between the width ratios given in equations (7)-(10) and the data. The experimental error bars are quite large, due to the propagation of errors in ratios of differences. It is likely that some of the systematics or statistical errors are correlated and will cancel in these combinations, but we did not pursue this possibility in absence of enough details on the experimental analyses. The same results, derived by excluding either E760 or CLEO from the fit, are also included in Table 3.

As a final exercise, we include in our analysis the effect of an effective gluon mass on the final state phase space. Following ref. [18], we applied a correction factor to the hadronic decay widths. Notice that contrary to 3S_1 decays, where the final state involves three gluons at LO, there are only two gluons at LO in $\chi_{0,2}$ decays. As a consequence, the impact of this correction is less significant. It is not clear to us what is the right procedure to extend this idea to decays to $q\bar{q}g$ final states. Since these are dominated by the soft gluon region, where the quarks carry most of the energy, and since this domain is already screened by the IR cutoff, we chose not to include any correction factor for these final states. We collect here the results of the global fit, which are only meant to be indicative of the possible size of these effects:

$$\alpha_s = 0.326 \pm 0.030 \quad \frac{|R'(0)|^2}{16m_c^4} = 0.69 \pm 0.11 \text{ MeV} \quad H_8 = 4.2 \pm 0.5 \text{ MeV} \quad (18)$$

$$H_1 = 15.8 \pm 2.0 \text{ MeV} \quad \chi_{fit}^2 = 6.6 \quad (19)$$

The most significant change is in the value of α_s , as already pointed out in ref. [18]. Notice also a slight improvement in the quality of the fit. We also mention that a clear prediction of the Consoli and Field approach is that the ratio of hadronic widths of χ_0 and

χ_2 should be insensitive to the effective gluon mass. The experimental value of this ratio is 7.9 ± 3.3 . The results of our fit from Eq.(11) yield a theoretical ratio of 5.4 ± 1.3 , those from Eq.(18) yield 6.4 ± 1.4 . Both results are in agreement with the data, the second one being slightly better because of the larger value of α_s .

In conclusion, we find that current data on 3P_J charmonium decays are well consistent with NLO perturbative QCD. The error bars are still large for more incisive tests of the theory, and leave room for deviations from the naive NR approximation and for higher order perturbative corrections. Nevertheless the agreement found is encouraging, and hopefully relieves serious concerns raised in earlier works. A reduction in the significant discrepancy found between the $\Gamma(\chi_{c2} \rightarrow \gamma\gamma)$ widths measured by different experiments will be of fundamental importance to guide the extraction of theoretical parameters from the data. Likewise, a new measurement of $\Gamma(\chi_{c0} \rightarrow \gamma\gamma)$ would be very helpful.

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Process	Γ (MeV)	Reference
$\Gamma(\chi_{c0} \rightarrow \gamma\gamma)$	$(4.0 \pm 2.8) \times 10^{-3}$	Crystal Ball [21]
$\Gamma(\chi_{c2} \rightarrow \gamma\gamma)$	$(0.321 \pm 0.095) \times 10^{-3}$	E760 [3]
$\Gamma(\chi_{c2} \rightarrow \gamma\gamma)$	$(1.08 \pm 0.38) \times 10^{-3}$	CLEO [5]
$\Gamma(\chi_{c2} \rightarrow \gamma\gamma)$	$(3.4 \pm 1.9) \times 10^{-3}$	TPC2 $_{\gamma}$ [4]
$\Gamma(\chi_{c0} \rightarrow LH)$	13.5 ± 5.4	Crystal Ball [21]
$\Gamma(\chi_{c1} \rightarrow LH)$	0.64 ± 0.10	E760 [1]
$\Gamma(\chi_{c2} \rightarrow LH)$	1.71 ± 0.21	E760 [1]

Table 1: Most recent experimental results on χ_c decay widths. The errors were obtained by combining in quadrature the statistical and systematic errors given in the quoted references. The widths to light hadrons were obtained from total widths by removing the contributions of known radiative decays.

Process	Data–Theory/Error
$\Gamma(\chi_{c0} \rightarrow \gamma\gamma)$	–0.44
$\Gamma(\chi_{c2} \rightarrow \gamma\gamma)$ (E760)	0.55
$\Gamma(\chi_{c2} \rightarrow \gamma\gamma)$ (CLEO)	–1.8
$\Gamma(\chi_{c2} \rightarrow \gamma\gamma)$ (TPC2)	–1.6
$\Gamma(\chi_{c0} \rightarrow LH)$	–0.74
$\Gamma(\chi_{c1} \rightarrow LH)$	–0.13
$\Gamma(\chi_{c2} \rightarrow LH)$	0.29

Table 2: Fractional differences, relative to the experimental errors, between data and theory predictions after the global fit.

	Theory			Data
	Global	No E760	No CLEO	
$\frac{\Gamma(\chi_{c0} \rightarrow \gamma\gamma)}{\Gamma(\chi_{c2} \rightarrow \gamma\gamma)}$	7.4 ± 0.8	5.7 ± 0.45	7.7 ± 0.9	12.5 ± 9.5 (E760)
				3.7 ± 2.9 (CLEO)
				1.2 ± 1.0 (TPC2)
$\frac{\Gamma(\chi_{c0} \rightarrow LH) - \Gamma(\chi_{c1} \rightarrow LH)}{\Gamma(\chi_{c2} \rightarrow LH) - \Gamma(\chi_{c1} \rightarrow LH)}$	7.7 ± 0.5	6.4 ± 0.4	7.9 ± 0.5	12.0 ± 5.7
$\frac{\Gamma(\chi_{c0} \rightarrow \gamma\gamma) \times 10^3}{\Gamma(\chi_{c2} \rightarrow LH) - \Gamma(\chi_{c1} \rightarrow LH)}$	2.4 ± 0.5	5.0 ± 1.5	2.2 ± 0.5	3.7 ± 2.7
$\frac{\Gamma(\chi_{c2} \rightarrow \gamma\gamma) \times 10^4}{\Gamma(\chi_{c2} \rightarrow LH) - \Gamma(\chi_{c1} \rightarrow LH)}$	3.3 ± 1.0	8.8 ± 3.4	2.9 ± 1.0	3.0 ± 1.1 (E760)
				10 ± 4 (CLEO)
				32 ± 19 (TPC2)

Table 3: Comparison between data and theory for ratios of widths (includes global fit, fit without E760 and without CLEO $\Gamma(\chi_{c2} \rightarrow \gamma\gamma)$ datum).